EFFECTOR ACTIVITY OF A HUMAN BEING IN FIXING PERFORMANCE TIME

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Among the tests for evaluating the functional capabilities of a human being on board a spacecraft an important role belongs to tests connected with monitoring operations. Good control of a spacecraft and the situation is possible only on the basis of a continuous and precise evaluation of information on changes in the /125
medium and in one's own activities. Hence, the value of research into the capabilities of man as a servosystem is clear. Given in the present paper are data on the operation of a human being under given time conditions. As will be shown, under such conditions man operates as a system which accomplishes a two-dimensional monitoring operation: of the given time and of the speed of his own actions. The methods applied in this research can be used as tests to evaluate the efficiency of a human operator as a servosystem.

The speed of motion is one of the essential variables of the effector activity of a human being: Speed is one of the components which determines the efficiency of execution, and therefore analysis of the mechanisms that regulate speed is important for an evaluation of human activity. There is another aspect which is in need of special consideration. This is an aspect incident to representation of time by a human being and to human activity to be accomplished within fixed time intervals.

Speed of motion (tempo) is a variable which involves the time and number of motions or individual motor acts. It can be defined both in terms of the numbers of motions within a certain unit of time as well as in terms of the time spent in accomplishing a certain fixed number of motions. A convenient representation of speed is the time interval within which a motor cycle is accomplished, since the interval will decrease as the speed increases. Such a representation is convenient because, on the one hand, it yields a criterion for the speed of motion and, on the other hand, it introduces the problem of time estimation into the scope of examination.

At the present time there are two opposing viewpoints as to the mechanism by which time is perceived and estimated. A number of investigators believe that estimation of time intervals is tied in with the perception of external signals [1, 10]. Another group of investigators suggest that time estimation is based on an interval process of generating intergals [11, 14]. In connection with the latter viewpoint, of great importance is the study of the natural effector activity of man within the estimated interval. The possibility of representing the human speed of motion in terms of time intervals paves the way for the assumption that speed of motion participates in time estimation.

All that has been said clarifies the meaning of the research into the effector activity of man within fixed time intervals as presented in the present article.

The subject matter of the experiments consisted in the repeated execution by test subjects, within a time interval fixed by the experimenter, of a thoroughly learned sequence of actions (pressing keys on a panel in a strict order) consisting of 24 individual motor acts. The questions which may be answered by such an experiment can be formulated as follows. /126

1. Inasmuch as the work to be done by the test subject is attendent upon a fixed overall completion time, he will have to keep track of the prescribed interval. How accurately can he do this?

2. Since the time of completion of a single motor cycle is not prescribed, we are not sure whether it is random or is fixed by the test subject himself.

3. If errors are made in keeping track of the interval, the question is what are their qualitative characteristics so as to determine the probability of estimating and compensating for them.

4. What is the character of compensation of errors committed in keeping track of the interval and is this character connected in some way with the speed of motions (the length of the interval during which a motor cycle is completed)?

METHOD

A detailed description of the experimental arrangement, of the principles on which the motor problems were based and methods of analyzing the results has been given in the preceding publications [4, 5, 6, 7].

The main portion of the present paper is devoted to studying the accomplishment of a series of actions with the time specified. In complementary experiments a study was made of the execution of a series in a given time, with the test subjects themselves estimating the errors, and of the distinction made by the test subjects in the prescribed intervals.

In the main series of experiments 15 test subjects of both sexes, volunteers, aged 18-45, with high-school or college education, participated.

The problem consisted of 24 sequential depressions of 8 keys on a panel. The order of actions was organized spatially taking into account the predetermined facts of grouping of individual actions. The order proposed in this study allowed for the possibility of organizing blocks of 3 or 6 actions. If the keys of the panel are numbered

1234
5678, the problem can be written as
1 5 6 4 8 7 3 2 7 2 3 6 8 3 4 5 2 1 7 6 1 6 7 4.

Experimental procedure. The test subject was informed of the key numbering system and received a sheet of paper on which the problem was written down numerically. Within 20-30 min the test subject learned by himself, from the paper, to reproduce the prescribed order of the actions from memory. After the

problem had been learned, the paper was taken away and the test subject was requested to execute the series at a rate of speed convenient to him. The experimenter determined the average time of completion, and then this interval was used as a fixed time for completing the learned sequence of actions. The experimenter gave the signal to begin work by flashing one of the lights on the panel. The signal for the end of the time interval was given by flashing another light. The test subjects executed the sequence of actions 30-100 times. /127

The instructions informed the test subject that is was necessary to complete the learned series of actions within the time interval, which was delineated by two light signals. The start of the last (24-th) motion (key-pressing action) must coincide with the start of the last signal.

The experiments with the test subjects evaluating their own errors (4 test subjects) were carried out under the same conditions, but with the additional instruction that the test subject was to evaluate the accuracy of his work each time he had completed a sequence. The statements were to be "earlier" if he beat the terminating signal, "later" if he did not succeed in finishing within the appointed time, "exactly" if he considered that the start of the last action coincided with the work termination signal. The responses were recorded.

Indexes. The execution of the learned series of actions was recorded on the tape of a loop oscillograph at a tape speed of 4-10 mm/sec; when the tapes were examined with a photoamplifier, it was possible to evaluate the time intervals with an accuracy of 50-20 msec.

In analyzing the tapes we measured the time intervals, which made it possible to get a complete time scan of the process of executing a sequence of actions by the following scheme:

1	2	3	4	...	47	48	49	50
Latent period-time from the initiation of the start signal by the experimenter until the test subject started his first pressing action	Duration of the first pressing action	Pause between the 1st and 2nd pressing action (hand transfer time)	Duration of the second pressing action	...	Pause between the 23-rd and 24th action	Duration of the 24th action	Total time of completion (sum of Nos. 1-47)	Error (time discrepancy between the beginning of the 24th action and the issuance of the 2nd signal by the experimenter

The measured intervals were calculated by row, each consecutive row corresponding to the next repetition of the sequence of actions in turn. Comparison of the magnitude and sign of the errors in each two adjacent rows of column 50 made it possible to determine whether there was error compensation relative to the prescribed time interval and how large the compensation was. /128

Pairwise comparison of the values for the duration of the intervals in adjacent rows of columns 1-48 permitted determination of the distribution of the magnitude of the compensation over the entire time it took to complete the problem.

The difference in the prescribed time intervals was investigated for three test subjects.

Experimental procedure. A light was turned on in front of the test subject, sitting behind the panel, for a definite period of time (from 4-36 sec). The differences in the duration of the successively generated intervals were 1,2,4,8, and 12 sec. The signals were supplied with an interruption of about 1 sec.

The test subject was requested to note the duration of the signal and to compare the duration of the prevailing interval with the preceding one. The estimate was announced with the words: "faster," "slower," or "the same." The instructions stated that it was not permitted to consciously count the time or to do anything else that would resemble such an action. The experiment was recorded continuously.

EXPERIMENTAL RESULTS

Magnitude of Errors and Degree of Their Compensation

In the main experiments 15 test subjects first solved the problem of keeping track of an interval. Each test subject repeated a sequence of actions in a given interval from 30 to 50 times.

In the secondary experiments 4 test subjects participated, each having experience in accomplishing the task of keeping track of an interval. Each repeated the sequence 90-100 times. In addition, in these experiments the test subjects had to make an estimate of how accurate their work was. Obviously, this facilitated a more effective solution of the interval monitoring problem. In this case the test subjects worked more accurately.

Of the 366 cases of repetition of the sequence in the secondary experiments, it was observed that errors, or deviations from the prescribed interval, were absent in 13 cases (3.6%). In 69 cases (18.9%) the error (on the lead or lag side) did not exceed 100 msec.

The mean value of the deviations from the interval was 260 ± 11 msec, which, in view of a specified of 13,00-1400 msec, does not exceed 2% of the error level.

In the main experiments (without estimating errors) tracking of the interval was less accurate. Given in Table 1 are data on the error distribution in this case (summed over the group of test subjects who completed the problem with a given interval of 15,000 msec; 8 people).

From the table it is evident that the greater portion of the errors (more than 60%), for both cases, lead and lag, lie within the range of 200-600 msec. The mean error for the case of lag was 726 msec, and for the case of lead it was 681 msec. At the given interval of 15,000 msec the average error was 4.8-4.5%. /129

TABLE 1. Relative Rate of Occurrence of Errors of Either Sign and Values for an 8-Man Group of Test Subjects

No. of cases	Error	Magnitude of error, msec						
		≤200	201–400	401–600	601–800	801–1000	1001–1200	1201–3000
Lag.....	294	0.14	0.36	0.15	0.13	0.07	0.05	0.10
Lead.....	195	0.17	0.23	0.21	0.09	0.07	0.09	0.14

Shown in Fig. 1 is the course of the interval-monitoring experiment for one of the test subjects. As evident from the figure, a continuous search is made during the experiment, with fluctuations on both sides of the interval. The extent of the fluctuations is relatively small; the majority of the deviations are compensated for in the next step (a deviation to one side alternates with a deviation to the other side). The shape of the curve is highly reminiscent of the fluctuation curve for an error-compensation feedback system.

In connection with the fact that the sequence of actions executed by our test subjects consisted of 24 uniform motor cycles and that the time of completion of the entire series, and not of only one cycle, was specified, we might ask what is the character of the distribution of the total time between individual cycles in the sequence of actions? We examined this question in [4]. In that investigation, in parts, we presented data obtained in experiments of the 1st series of the present report.

It was found that the overall time of fulfillment of a sequence is distributed uniformly over all 24 actions. In view of this fact it was conjectured that the uniformity of execution of a sequence of actions is governed by the operation of an internal generator which controls the time of completion of a single motor cycle.

A corollary of this hypothesis, which was confirmed in our experiments, is the argument that monitoring of a specified time interval must be attendant upon some sort of adjustment of the interval generator which controls the time of a motor cycle or, in other words, time is monitored by searching for the frequency of motion and monitoring this frequency. /130

The term "time monitoring" was introduced by M.A. Alekseyev [2] for cases when man must accomplish a certain task within time intervals controlled externally. Under such conditions, which prevailed in our experiments also, each person was required not only to accomplish the necessary actions in a required order, but also to space them out over a specified time interval in such a way as to cover the

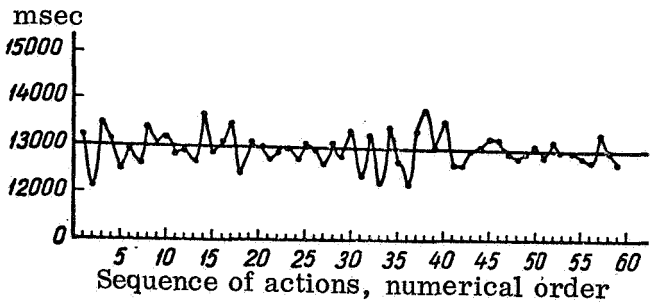

Figure 1. Monitoring of a Specified Time Interval (Test subject P-v). Horizontal Line-the Specified Interval (13,000 msec).

interval. It is only natural that in carrying out this task it is necessary somehow to keep track of the time. It is possible to find out precisely how this process is done by investigating the time-error compensation process. We carried out such an investigation by pairwise comparision of all cases when an appreciable decrease in error was observed in the repetition following the one in which an error was committed (the test of "appreciable" was a decrease in error of $\geqslant 30\%$ its magnitude). /131

Given in Table 2 are the composite data characterizing the dependence of the compensation rate on the magnitude and sign of the error for the group of test subjects who participated in the principal experiments.

TABLE 2. Relative Frequency of the Cases of Compensation or Aggravation of an Error as a Function of the Magnitude and Sign of the Error in the Preceding Repetition of the Sequence

Error category	Magnitude of the errors, msec							
	⩽200	201—400	401—600	601—800	801—1000	1001—1200	1201—2000	Total
Lag errors								
No. of cases	42	105	43	37	20	14	33	294
Compensation, % ...	19	36	40	43	70	71	70	
Aggravation, %	62	37	33	11	15	7	6	
Lead errors								
No. of cases	33	46	41	17	14	18	26	195
Compensation, %.....	30	55	47	53	50	83	81	
Aggravation, %	42	21	34	17	21	6	4	

Presented in Fig. 2 are curves demonstrating the dependence of the magnitude of the compensation and of the aggravation of the error on the magnitude of the error.

As evident from the table and figure, there is a distinct relationship between the magnitude of the errors and the degree of its compensation. Clearly evident are three zones characterizing the degree of error compensation: deviations of less than 200 msec are practically uncompensated; deviations of 200-800 msec for the case of lag and of 200-1000 msec for lead are compensated in approximately

half the cases (zone of partial correction); deviations exceeding 800 or 1000 msec are compensated in the majority of cases (zone of satisfactory correction). A decrease is observed in the number of cases of error aggravation as the number of errors increases.

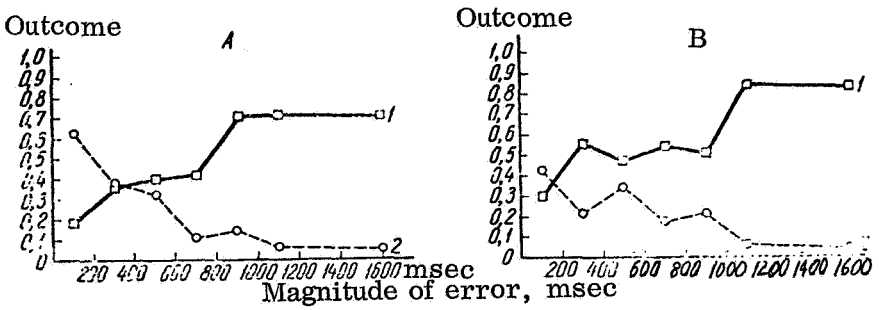

Figure 2. Probability of Compensation (1) or Aggravation (2) of Error in Completing a Sequence of Actions as a Function of the Deviation from the Specified Interval in the Preceding Repetition for the Cases of Lag (A) or Lead (B).

Thus, the phenomenon of error compensation in related to the magnitude of the deviation from the specified time. On the other hand, the character of the curves showing an increase in the number of compensated errors for errors of different sign (lead and lag errors) reveals a distinct similarity and indicates that the phenomenon of error compensation does not depend on the sign of the error.

Character of Error Compensation /132

Since we have no knowledge whatever of the distribution of error compensation over the time of completion of a sequence, of the dependence of this distribution on the sign of the error, or on its magnitude, we attempted to examine this question from these viewpoints. Given in Table 3 is an analysis of 240 cases of compensation (all cases where the error was sufficiently large and its compensation was complete and distinct); the method of pairwise comparison of intervals was used to establish the differences representing a measure of the extent to which individual time segments of the sequence participated in compensation. Considered in the table are the dependence of the character of the compensation on the sign of the error and the three methods of compensation to which all the the examined cases reduced. Special attention was devoted to the differences in the first time segments of completion of the sequence.

The reason why we proceeded in this fashion was that we expected two possible analytical results:

1) error compensation is accomplished as a result of a difference in latent period or in the initial time of completion; the overall tempo of completion will not be changed (the case when the internally controlled interval does not take on a new value);

2) error compensation is uniformly distributed over a large number of motor cycles (the cases when the internally controlled interval takes on a new value).

From Table 3 the following is evident:

1) the character of the compensation and its distribution are approximately the same for errors of either sign;

2) the latent period and the start of execution of a sequence are not the most responsible for compensation of the execution of a sequence by sections;

3) error compensation is uniformly distributed either over the entire period of the sequence or over approximately half the period of the sequence;

4) half of all cases are made up of compensation uniformly distributed over the entire sequence of actions.

It must be noted that the sum of the differences in the intervals given in each row is less than the total magnitude of the compensation, since values representative of the last three actions of the series are absent. The time of completion of these actions was not taken into account because this time may have been affected by the signal for termination of the given interval and is superimposed on the compensation of the preceding error. Therefore, the column "first half of the sequence" includes the time of completion of the 4th to 12th actions, while the column "second half of the sequence" includes that of the 13th to 21st actions.

In view of the fact that the compensation method as well as the very circumstance that compensation occurred proved to be independent of the sign of the error, composite data on compensation, ignoring the sign of the error, will be given in the rest of the presentation. /134

Since the case of uniform distribution of compensation over the entire period of the sequence of actions is of the greatest interest for purposes of determining changes in the value of internally controlled intervals, the subsequent analysis of the distribution of differences was carried out on the basis of precisely three cases. We analyzed 111 cases of uniform distribution of error compensation (Table 3 contains a total of 125 such cases, but in 14 cases we detected technical defeats in the records which prevented inclusion of these cases in a more detailed analysis). The entire sequence of actions was divided into 4 equal segments of 6 actions each; analyzed were the pairwise differences in each of the segments, then one of these segments (the second in the sequence) was analyzed with respect to each of the smallest segments of execution, i.e., with respect to all the pressing times and all the pauses between consecutive motions. /135

We computed the differences in time of completion in each of the segments; the first segment belonged to performance with an error, the second to performance with error compensation (Table 4, A, B).

As evident from the tables, the total value of compensation is distributed uniformly over the entire time of completion of a sequence, even down to change

TABLE 3. Distribution of Error Compensation with Respect to the Time of Completion of a Sequence

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Character of compensation	No. of cases	Magnitude of the error msec	Magnitude of the compensation msec	Magnitude of difference in various execution intervals, msec			
				latent period	first three actions	first half of sequence	second half of sequence
Lag error							
Uniform over the entire sequence	65	977±96	1323±66	87±28	144±30	547±21	542±50
Uniform in the first half of the sequence	41	628±87	992±155	112±33	163±57	844±149	—233±83 *
Uniform in the second half of the sequence	25	1192±252	1370±235	70±40	12±61	—14±123 *	1262±197
Lead error							
Uniform over the entire sequence	60.	845±95	1196±124	37±17	152±30	466±71	547±78
Uniform in the first half of the sequence	27	793±140	748±82	124±34	180±34	642±109	—226±73 *
Uniform in the second half of the sequence	22	993±119	1041±139	59±37	77±28	—168±48 *	1082±133

*Cases when the error is aggravated rather than being compensated.

TABLE 4 (A). Distribution of the Magnitude of Compensation Over Segments of the Sequence (111 cases) (Mean Value of the Error, 892 msec; Mean Value of the Compensation, 981 msec)

Segments of the sequence	Magnitude of compensation (msec)	Fraction of the total value of compensation	Error residue after compensation by the respective segments
I (motions 1-6)	305	0.3	587
II (motions 7-12)	265	0.27	322
III (motions 13-18)	268	0.28	54
IV (motions 19-24)	148	0.15	-94

TABLE 4 (B). Distribution of the Magnitude of Compensation Over the Time of Execution of Motor Cycles and Their Elements in the Second Segment of the Sequence (111 cases)

Numerical position of the motor cycle in the sequence	Magnitude of the compensation for cycle (msec)	Fraction of the compensation of the entire segment	Magnitude of the compensation for pressing time (msec)	Magnitude of the compensation for the pause between pressing actions (msec
7	41	0.15	18	23
8	30	0.1	15	15
9	65	0.24	20	45
10	55	0.2	12	43
11	34	0.11	16	18
12	40	0.15	15	25

in the value of the duration of each pressing action and of each pause between consecutive actions. Particular attention should be paid to the high uniformity of these changes, indicating that the error compensation mechanism is incident to variation in the mean value of the interval during which one motor cycle is completed. In the light of what has been previously said, this means that the mechanism controlling the speed of motion (the interval generator) is responsible for compensation. In this connection the mean value of compensation for one motor cycle is deserving of attention. From the data given in Table 4 (B) it is not difficult to compute that the mean value of the change in interval of a motor cycle is 44 msec. Let us note this figure and go on to consider the question of the dependence of the compensation method on the magnitude of the error. As has already been said, analysis resulted in the discovery of three possible methods, covering the majority of cases: 1) uniform compensation, when the magnitude of the error with a minus sign was equally distributed over all the motor cycles falling within the time of execution of the sequence during which the preceding error is compensated; 2) compensation of the first half, when complete error compensation was accomplished already halfway through the next sequence, and then compensation stopped; 3) compensation of the second half, when the rate of execution of the first half of the sequence, all of which was taken up by error correction, did not differ from the rate of execution of the

preceding (error-generating) run, and in the second half a sharp shift occurs, leading to compensation at the end of the period.

All the cases referring to one or the other of the compensation methods were broken down into groups as a function of the magnitude of the error, and their mean values were computed. The groups were associated with errors of the following values: 1) large errors (about 2,000 msec); 2) moderate errors (about 1,000 msec); 3) small errors (about 500 msec). The results of the analysis are given in Tables 5,6,7. The tables were compiled as follows: after the errors had been arranged in groups, we averaged the pairwise time differences of 12 segments between the sequences in which the working speed gave rise to the error and the next sequence in which the error was compensated. These differences were represented as the total residue of the error after completing the given segment of the sequence. /137

The speed of completion of the segment may be the same as in the preceding sequence (if so the magnitude of the error residue remains unchanged), may change in favor of error compensation (magnitude of the error compensation decreases) and, finally, may change in favor of error aggravation (magnitude of the error residue increases). In the right-hand columns of the tables these quantities are expressed in %. The total magnitude of the error (regardless of its specific value) is taken as 100; the attainment of complete compensation as 0; quantities with a "minus" sign reflect the process of overshoot of zero and accumulation of an error of the opposite sign.

The following is evident from these tables: /138

1) the decrease in error during the compensation process is a slow affair and is attendent upon the completion of no less than one half the sequence of actions during which compensation takes place;

2) when the errors of various gradations (large, medium and small) we run up against all the enumerated compensation methods;

3) when estimating errors as percentages (when the magnitude of the error is leveled off) it is found that the compensation method has approximately the same characteristics (Table 5, lines 1-6; Table 6, lines 1-6 and lines 9-11; Table 7, lines 7-11).

Of the greatest significance is the fact that all three compensation methods were found for errors of the various magnitudes, indicating that the compensation method does not depend on the magnitude of the error.

Shown in Fig. 3 are graphic representations of the above-mentioned three error-compensation methods, regardless of the magnitude of the error (we took the average values of the percentages of errors in Tables 5,6, and 7 for errors of the various groups). Deserving of attention is the change in nature of the curve during the process of compensation, and is especially noticeable in the case of compensation in the first half.

This change testifies to the change in working speed (readjustment of the interval being controlled) during the execution process and raises the question of

TABLE 5. Distribution of Error Compensation Over the Time of Completion of Individual Motor Cycles as a Function of the Magnitude of the Error

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Magnitude of the errors at various times during the the correction process	Large errors (msec)	Medium errors (msec)	Small errors (msec)	Large errors %	Medium errors %	Small errors %
Magnitude of the error	1960	1100	555	100	100	100
Residue after compensation in the latent period + cycle 1	1740	860	400	89	78	72
Residue after compensation in the latent period + cycles 1, 2, 3	1490	825	350	76	75	63
Residue after compensation in the first five cycles	1250	715	250	64	65	45
Residue after compensation in the first 7 cycles	1050	610	130	54	56	24
Error residue after 9 cycles	890	470	55	45	43	10
Error residue after 11 cycles	675	350	-95	34	33	-17
Error residue after 13 cycles	512	250	-225	26	23	-41
Error residue after 15 cycles	40	262	-330	2	24	-60
Error residue after 17 cycles	-75	135	-305	-4	12	-55
Error residue after 19 cycles	-87	-50	-480	-5	-4.5	-87
Error residue after 21 cycles	-240	-240	-570	-12	-22	-103
Error residue after 23 cycles	-100	-150	-440	-6	-14	-79
Total magnitude of the compensation in 23 cycles	2060	1250	995	106	114	179
Average value of the compensation for one motor cycle (msec)	83	50	40			

the criteria by which man is guided in the running process of monitoring his working speed. The inflection point on this curve lies below the zero line. This may mean in the evaluation by man that the corrections he introduced into the speed of execution are too large and he begins to reduce them.

Now let us return to the magnitude of the compensational increment per motor cycle. Above we wrote that the average increment (for errors of the

TABLE 6. Distribution of Compensation Over the Time of Completion of a Sequence in Those Cases When Correction Predominated in the First Half of the Work Period

Magnitude of the error at various instants of the correction process	Medium errors (msec	Small errors (msec)	Medium errors (%)	Small errors (%)
Magnitude of the errors	1080	450	100	100
Residue after the latent period + cycle 1	620	330	57	73
Residue after 3 cycles	455	285	42	63
Residue after 5 cycles	255	225	24	50
Residue after 7 cycles	115	100	11	22
Residue after 9 cycles	-145	-15	-14	-3
Residue after 11 cycles	-270	-30	-25	-7
Residue after 13 cycles	-395	-50	-37	-11
Residue after 15 cycles	-345	-75	-31	-17
Residue after 17 cycles	-420	-45	-39	-10
Residue after 19 cycles	-420	-70	-39	-16
Residue after 21 cycles	-435	-55	-40	-12
Residue after 23 cycles	-300	-15	-28	-3
Total magnitude of compensation in 23 cycles.....	1380	465	128	103
Average value of the compensation per motor cycle	80 (cycles 2-13)	43 (cycles 2-9)		

various magnitudes and for uniform compensation) is 44 msec. From Table 5 it can be seen that the average values of the increment for various cases are 83, 50 and 40 msec with uniform compensation, where 83 msec is the increment for compensating large errors, 50 for medium deviations and 40 for small deviations. The magnitudes of the increment were computed in Table 6 for the same part of the curve that reflects a shift in compensation. For this purpose we took the maximum magnitudes (from 1, 080 msec for medium errors of the total magnitude of the error up to 395 msec of the opposite sign, i.e., points where curve inflection began) and the total magnitude of the compensation was spread over the number of cycles in which compensation occurred.

It was found that the shifts for one cycle amount to 80 and 40 msec. Shifts for a single motor cycle were obtained in the same way from Table 7. From the table it is evident that for various gradations in the values of the error these shifts amount to 136, 84 and 45 msec. Thus, the increments reduce in all cases to three values: 1) 40-45; 2) 80-84 and 3) 136 msec. Perhaps it is not accidental that the magnitude of the increment in the second and third gradations corresponds to double and triple the value of the smallest increment.

To solve the question of the mechanisms responsible for compensation of the deviation from the given time, it is useful to clarify the part played by human evaluation mechanisms relative to errors themselves and to time intervals.

TABLE 7. Distribution of Compensation Over the Time of Completion of a Sequence in Those Cases When Correction Predominated in the Second Half of the Work Period

Magnitude of the error at various instants of the correction process	Large errors (msec)	Medium errors (msec)	Small errors (msec)	Large errors (%)	Medium errors (%)	Small errors (%)
Magnitude of the errors	2125	1120	530	100	100	100
Residue after the latent period + cycle 1	2175	1330	530	102	119	100
Residue after 3 cycles	2155	1300	480	101	116	91
Residue after 5 cycles	2100	1380	510	99	123	96
Residue after 7 cycles	2050	1300	540	96	116	102
Residue after 9 cycles	2075	1210	530	98	108	100
Residue after 11 cycles	2025	1100	520	95	98	98
Residue after 13 cycles	1925	1020	360	91	91	68
Residue after 15 cycles	1600	750	360	75	67	68
Residue after 17 cycles	1050	740	310	49	66	58
Residue after 19 cycles	750	630	270	35	56	51
Residue after 21 cycles	300	550	80	14	49	15
Residue after 23 cycles	175	100	-20	8	9	-4
Total magnitude in 23 cycles	1950	1020	550	92	91	104
Average value of the compensation per cycle (from the 10th to the 23rd)	136	84	45			

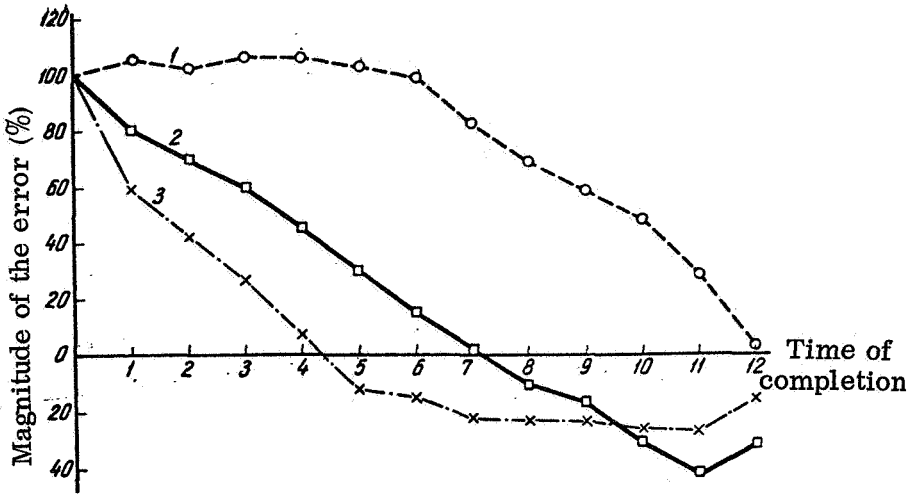

Figure 3. Character of the Compensation of Deviations from the Prescribed Interval (distribution of the increment which corrects the error over the time of the next repetition after the error):

1—Compensation in the Second Half of the Sequence; 2—Uniform Compensation; 3—Compensation in the First Half of the Sequence.

Error Estimation (deviations from the prescribed interval)

As already mentioned above, in these experiments four test persons repeated a large number of times (90-100) the well-known (to them) problem of 24 key-pressing actions on a panel within a given time interval (13.0-14.0 sec). After each repetition they estimated the degree of coincidence between their work and the time-controlling signal (remember that complete agreement required coincidence between the start of the 24th pressing action and the signal announcing the end of the given segment).

A correct estimate of a deviation error was considered to be a recognition of the sign of the error (in terms of "ahead" and "behind"). While recording the working time on the tape the error was measured and compared with the estimate. The results of this comparison are presented in Table 8, which contains the frequency of the correct estimates as a function of the magnitude of the deviation. In all 351 cases from 364 measurements were examined in the table. An absence of deviations was observed in 13 cases, and therefore they were not entered in the table.

To evaluate the significance of the figures given in the table, it is necessary to keep in mind that the test subject had the capability of choosing one of three responses.

Hence, in a completely random process, when the test subject does not discriminate between the presence or absence of an error, three equally probable

responses exist ("exactly," "behind," and "ahead"), one of which proves to be correct. Therefore the frequency of correct estimates up to 33% must be considered as the level of absence of correct estimates and only large frequencies need be taken into account. Within such a framework of reference, it is evident from Table 8 that errors of up to 100 msec are not evaluated by the test subjects. /141
Errors of 100-150 msec are possibly evaluated. It is even more probable (62% correct estimates) that errors of 150-200 msec are evaluated, and all errors of 200 msec and greater are correctly estimated in all cases. Thus, it can be considered that the magnitude of 150-200 msec is the threshold for estimating mismatch errors between the actions themselves and the given time. This magnitude is considerably lower than the one at which error compensation is good (800-1000 msec, when the error compensation reaches 70-80%; Table 2). This means that the compensation threshold and the estimation threshold do not coincide, and the mechanism of estimating mismatch errors cannot be the only factor responsible for error compensation.

TABLE 8. Estimation of Characteristic Errors as a Function of the Magnitude of the Deviation from the Given Interval

Magnitude of the deviation (msec)	Number			Magnitude of the deviation (msec)	Number		
	Cases	Correct estimates	Correct estimates in % of the no. of cases		Cases	Correct estimates	Correct estimates in % of the no. of cases
20-100	68	15	22	201-300	78	78	100
101-150	45	20	44	301-500	60	60	100
151-200	49	39	62	above 500	51	51	100

Estimation of Differences in Intervals

In view of the fact that the literature contains data relating to the dependence of the threshold of time-interval discrimination on the magnitude of the intervals [3], our experiments on discrimination of intervals were set up in the following manner. Intervals of 8, 16, and 24 sec were taken as the initial intervals relative to which discrimination was determined. The discrimination thresholds were examined in these limits in order to be able to analyze them both in terms of absolute value (in sec) and infractions of the initial interval. For this purpose, in the 8-sec interval we used comparison intervals differing by 1, 2 and 4 sec, both on the greater and smaller sides. In the 16-sec interval, intervals differing by 1, 2, 4 and 8 sec from the original (on both sides) were used for discrimination. For the 24-sec interval we used differences of 1, 2, 4, 8 and 12 sec on both sides. The intervals were prescribed by a device which made it possible to turn on a continuous light signal of the given duration, the error not exceeding 10 msec.

Each time the appropriate signal was given, the test subject had to compare it with the preceding one and make one of three responses relating to how he estimated the comparison (equal, shorter or longer). The results of this experiment

are given in Figs. 4 and 5, which contain 143 estimates of the above-described intervals by three test subjects.

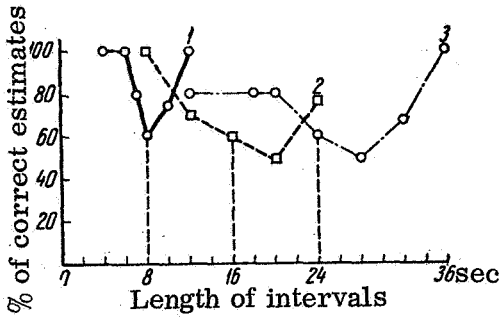

Figure 4. Discrimination of the Lengths of Intervals as a Function of Their Original Value.

Discrimination of Intervals as Compared with Intervals of 8(1), 16(2), and 24 sec (3).

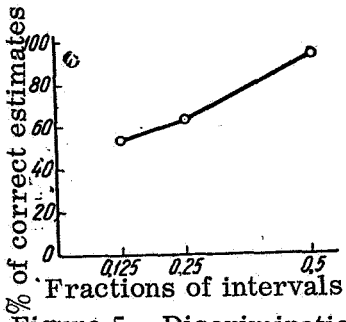

Figure 5. Discrimination of the Lengths of Intervals for Differences of 1/8, 1/4, and 1/2 of the Original Intervals.

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From Fig. 4 it is evident that the 8- sec interval is distinguished from the 6-sec and 10-sec in 100% of the cases. The curve has a sufficiently steep slope on both sides. At the 16-sec interval the discrimination curve has a more diffuse character; 100% of the correct comparison estimates were observed only in the case of decrease of this interval by 8 sec; 80% correct estimates were observed when the interval was increased by the same amount. The 24-sec interval was not so well distinguished from larger and smaller intervals as the preceding ones. The discrimination curve is spread out; 100% discrimination was observed when the interval was increased by 12 sec; 80% correct estimates were observed when the interval was decreased by 12 sec.

These results forces on us the idea that the threshold for distinguishing the length of a signal depends on the absolute value of the signal. In all cases when the interval being compared differs by 1/2 from the original interval, discrimination between the two intervals is good. This relationship is true for all three of the intervals used and is shown in Fig. 5, which presents data on the discrimination of two intervals, summed for all cases, where the difference between the compared intervals is expressed in fractions of the original interval.

Since all the preceding experiments were performed primarily at intervals close to the 16-sec interval, it is precisely this interval which is of greatest interest to us. From the curve in Fig. 4 it is evident that discrimination of intervals differing by 2 sec amounts to 40-70%, while complete discrimination is observed at a difference of 8 sec. At the same time, as we wrote earlier, complete error compensation with respect to the specified interval, when rhythmic activity is carried out during this interval, is observed when the deviation is about 1 sec. Thus it is doubtful whether the mechanism by which the length of a specified interval is estimated participates in error compensation.

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CONCLUSION

The data obtained in our experiments concern the problem of regulating the time characteristics of motion in man. In particular, they yield grounds for discussion of two questions:

1) possible interpretations of the fact that an error relative to a specified interval is compensated;

2) consequences ensuing from the qualitative characteristics of compensation.

Let us consider the experimental results in the light of the first question. It has been demonstrated that man executes a sequence of 24 actions while adhering to a specified (fixed) time interval and not deviating from this interval by more than 2-5%. It has also been demonstrated that errors of this dimension are compensated in the next repetition of the sequence. The overall time pattern (rhythm) of execution of the sequence remains constant under these working conditions, a fact which was examined in detail in some of our other papers.

Moreover, in this situation there exists a certain fixed interval for execution of a single motor cycle, the values of this interval changing by no less than 40-50 msec during compensatory adjustments. This implies that we are dealing here with three levels of the control process:

1) adjustment of the execution of the entire motor problem to an externally prescribed time interval;

2) control of the intervals of segments of the problem in conformity with a problem stored in the memory (execution of a program of ordered actions);

3) control of the frequency of responses, resulting in overall compensatory adjustment of the entire time of execution.

Only the first of these levels deals with an external, time-gauging signal; the remaining two are obviously connected with the operation of interval mechanisms of the central nervous system which measure and specify the frequency and rhythmic pattern of individual motor cycles.

It is natural to assume that the described levels do not cover the entire list of /144
levels in controlling the time characteristics of motion.

Here we are dealing with high control levels which issue general, undetailed instructions. Completely outside the framework of our examination are such levels as instructions on the speed of hand transfer in a direction toward the key to be pressed and in the reverse direction or instructions on the time correlation of contraction of individual muscles, or, finally, control of the time characteristics of individual motor acts.

The facts we have discovered relating to error compensation with respect to a specified interval and to compensatory adjustments affecting each motor cycle more or less uniformly permit us to draw some conclusions as to the characteristics of the processes underlying the above facts in the light of the theory of servosystems.

Application of this theory to the effector activity of man has been examined in detail by Adams [8] who believes that any human activity oriented toward eliminating errors of mismatch with an externally specified signal is a servosystem activity controlled over feedback channels by the magnitude of the mismatch error. At the same time Adams distinguishes between one- and two-dimensional monitoring systems, meaning by the latter, systems which are required to monitor two independent signal sources. Two-dimensional tracking systems are complex (especially in cases of bisensory tracking) and have hardly been studied.

Within the framework of these viewpoints, the problems of our test subjects are viewed as problems of monitoring a specified interval. The experimentally obtained characteristics of error compensation induce us to believe that we are dealing with a two-dimensional monitoring problem. The fact is that the test subjects accomplished error compensation by changing the frequency of the motor cycles. In order to do this it is necessary to fix in the memory not only the dimension of the given interval, but also the frequency of one's own motions. Consequently, the input of the given servosystem must be supplied with two signals; 1) the signal of mismatch in the time of completion of the last action and the end of the specified interval, and 2) the value of the frequency of the responses, on which depends the total time of execution; the detected mismatch with the specified interval.

The second question which it is expedient to discuss in connection with the results of our experiments deals with compensation mechanisms, in the light of establishing a link which is most responsible for this process. In the experiments it was determined that the thresholds of estimation of errors, of error compensation, and of discrimination between specified intervals do not coincide. Personal error is detected at a magnitude of 150-200 msec, is compensated at a value of 400-1000 msec, and the specified interval is distinguished from a different size interval at a difference of 4000-8000 msec. It must be imagined that neither an estimate of personal error nor an estimate of the specified interval as a whole can be the solely responsible links in the compensation process. The necessary missing link is a system which evaluates and controls the frequency (speed) of motion. /145

The literature contains a considerable quantity of data testifying to the fact that the personal frequency of motion is controlled and is conducive to accuracy in executing the motor problem [9, 12,13, 15]. On the other hand, some authors assert that control of the time distribution of responses is due completely to externally provided signals [2].

It is believed that there will be good agreement between the various viewpoints if the ideas we presented are accepted, namely, two-dimensional monitoring of signals carrying information about time, of the external signal, and of the frequency of personal motions.

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